arTeMiDe

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MCEGs for future ep and eA facilities
Regensburg
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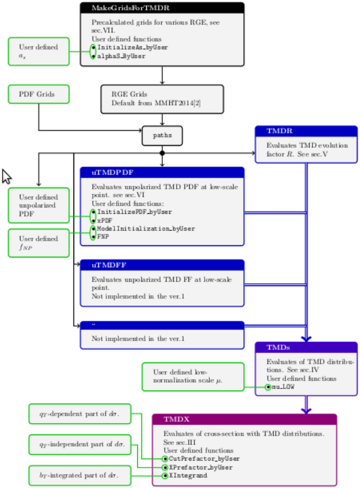
arTeMiDe



General description

arTeMiDe is the library for operation with TMD distributions, TMD evolution and TMD cross-section.

Developer: A.Vladimirov
Available at: https://teorica.fis.ucm.es/artemide

- FORTRAN 90 code
- Module structure
- Plenty of user-defined options
- Efficient code ($\sim 10^9$ TMDs $\sim$ 6. min at NNLO)
- The version 1.1 has been (partially) benchmarked with APFEL++ (thanks to V.Bertone)

Version 1.1

- unpolarized TMD PDFs (at all known PT orders)
- universal TMD evolution (at all known PT orders)
- Drell-Yan "like" cross-section

TMD factorization is a complicated composition
of perturbative and non-perturbative functions.

$$\frac{d\sigma}{dX} \simeq \int db e^{ibq_T} H(Q) \quad \{R(Q \to (\mu_i, \zeta_i))\}^2 \quad F_1(x, b, \mu_i, \zeta_i) F_2(x, b, \mu_i, \zeta_i)$$

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Hard coef.
Perturbative

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Hard coef. ($H(Q)$)
Perturbative

Evolution factor ($\{R(Q \to (\mu_i, \zeta_i))\}^2$)
γ_F $\mathcal{D}(b)$

UV anomalous dimension (γ_F)
Perturbative

Rap. anomalous dimension ($\mathcal{D}(b)$)
$b \ll \Lambda^{-1}$ **Perturbative**
$b \gtrsim \Lambda^{-1}$ **Non-Perturbative**

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$H(Q)$ — Hard coef. **Perturbative**

$\{R(Q \to (\mu_i, \zeta_i))\}^2$ — Evolution factor: γ_F, $\mathcal{D}(b)$

- γ_F — UV anomalous dimension **Perturbative**
- $\mathcal{D}(b)$ — Rap. anomalous dimension
  - $b \ll \Lambda^{-1}$ **Perturbative**
  - $b \gtrsim \Lambda^{-1}$ **Non-Perturbative**

F_1, F_2 — TMD distributions **Non-Perturbative**

at $b \ll \Lambda^{-1}$ **OPE to collinear**

$$F = C \otimes f \cdot f_{NP}$$

C is **Perturbative**

f is **Non-Perturbative**(known)

f_{NP} is **Non-Perturbative**

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Balance

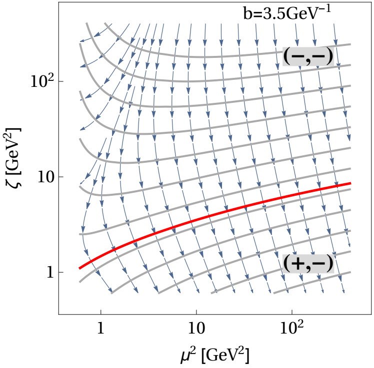
	Perturbative	**Non-Perturbative**	
H	Hard coeff.	collinear distributions	$f, d, ..$
γ	UV anomalous dimension	TMD behaviour	f_{NP}
$\mathcal{D}$	rap. anomalous dimension	rap. anomalous dimension	$\mathcal{D}_{NP}$
C	mathing coefficients		

ζ-prescription and optimal TMDs

arTeMiDe is based on the ζ-prescription

$$F(x,b;\mu_f,\zeta_f) = R[(\mu_f,\zeta_f) \to (\mu_i,\zeta_i)]F(x,b;\mu_i,\zeta_i)$$

ζ-prescription consists in particular selection of scales (μ_i,ζ_i) where TMD distribution scaleless.



$$\mu \frac{d}{d\mu} F(x,b;\mu,\zeta_\mu) = 0$$

- $F(x,b)$ **optimal TMD**
- Very convenient practically
- Reduces theory errors
- Universal
- Not a model.
- [I.Scimemi,AV,1706.01473; 1803.????]

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unpolarized TMD PDF

uTMDPDF.f90

Input: collinear PDFs, α_s
Optional input: $f_{NP}(x,b)$, $\mu_{\rm OPE}(x,b)$ (by default values from our NNLO extraction)
Output: unpolarized TMD in ζ-prescription

$$F(x,b) = C(x,\mathbf{b},\mu_{\rm OPE}) \otimes \Big(f(x,\mu_{\rm OPE}) f_{NP}(x,\mathbf{b})\Big)$$

Example code

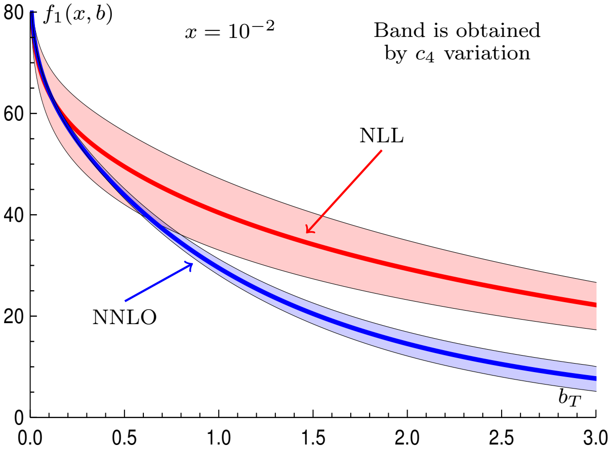
```
use uTMDPDF
call uTMDPDF_Initialize('NNLO','NNLO','NNLO')
TMD=uTMDPDF_lowScale50(x,bT)
```

Gives vector ($\bar{b}$,$\bar{c}$,....,c,b) of unpolarized TMD

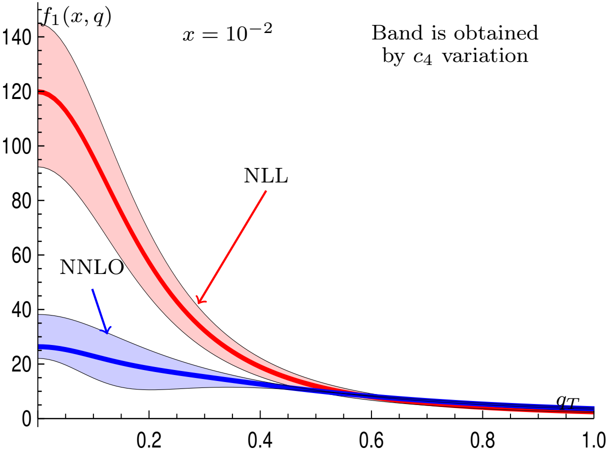
Optimization

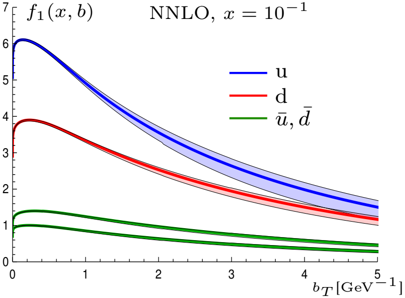
Code is numerically accurate (adaptive Gauss-Kronrod), therefore for multi calls I suggest to use griding (build in).

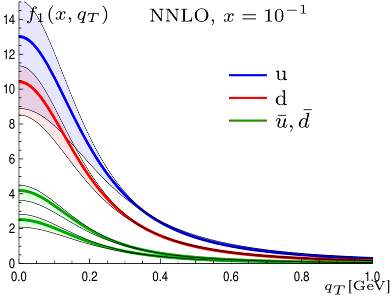
Uncertainties in TMD



Uncertainties in TMD







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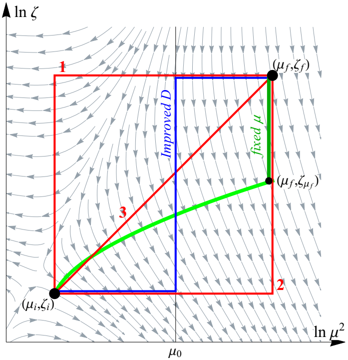
Evolution factor

$$R[b;(\mu_f,\zeta_f)\to(\mu_i,\zeta_i)] = \exp\left[\int_P \left(\gamma_F(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}(\mu,b)\frac{d\zeta}{\zeta}\right)\right]$$



TMDR.f90

Input: α_s
Optional input: $\mathcal{D}_{NP}(b)$, μ_0 (by default values from our NNLO extraction)
Output: $R(b;\mu_1,\zeta_1,\mu_2,\zeta_2)$

- "Classical" option is solution 1
- More to come in ver.1.2 [I.Scimemi,AV; 1803.????]
- R is universal for all TMDs
- Unfortunately there is an ambiguity (theory bug) which gives rather large error band

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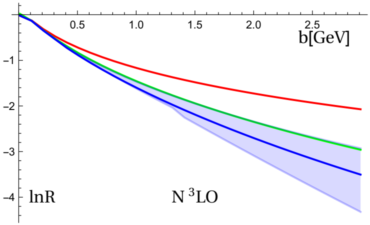

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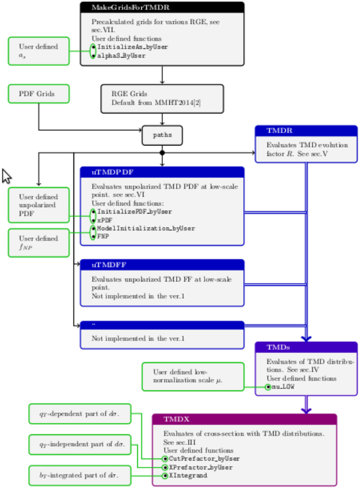


TMDs.f90

Joint interface to lower arTeMiDe modules.

TMDX_DY.f90

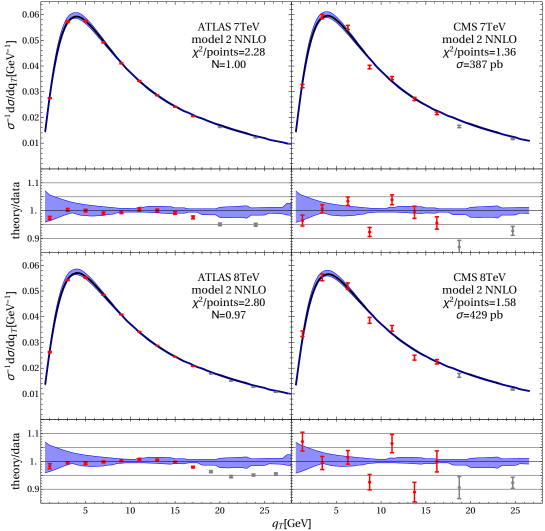
Evaluation of DY-like cross-section (2 TMD-PDFs)

$$\frac{d\sigma}{dq_T dy dQ^2} \sim \int bdbJ_0(bq_T)F_1(x,b)F_2(x,b)$$

- Integration by Ogata quadrature (best for the Hankel type integrals).
- All possible combinations of phase space integration
- Scale variations

There is a problem of user interface. There are too many options. But I am working on it.

$q_T < 0.2Q$



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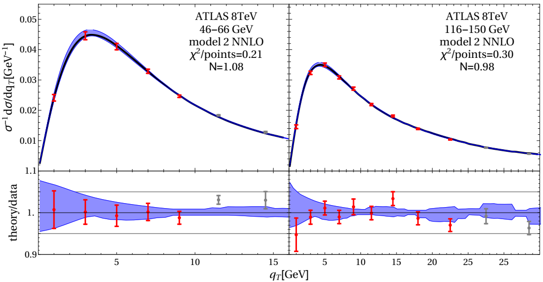
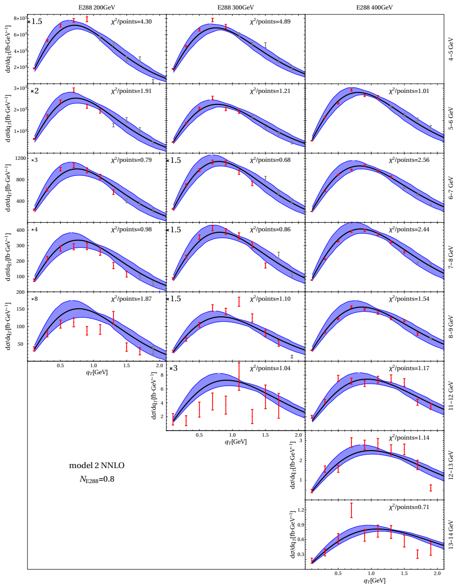


ATLAS 8TeV
46–66 GeV
model 2 NNLO
χ²/points=0.21
N=1.08
ATLAS 8TeV
116–150 GeV
model 2 NNLO
χ²/points=0.30
N=0.98
σ⁻¹dσ/dq_T[GeV⁻¹]
theory/data
q_T[GeV]

$q_T < 0.2Q$



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Current and future development

arTeMiDe is the only (public) code for operation within TMD factorization
arTeMiDe is the only (public) code which includes the latest theory achievements (2-loop matching, 3-loop evolution, etc)

Version 1.2

Currently under tests

- uTMDFFs (LO,NLO,NNLO)
- SIDIS cross-sections (LO,NLO,NNLO)
- New evolution factors
- Plenty of optimizations

Future plans

- Include all polarized TMDs
- And polarized cross-sections
- Global fit (TMDPDF+TMDFF)